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Basins and barrels: the geological background to the search for fossil fuels in Western Australia

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Abstract

Fossil fuels, i.e. petroleum and coal, occur in (mainly Phanerozoic) sedimentary basins. The geology of these basins can best be understood in terms of plate tectonics—a concept which has revolutionised geological thinking. Western Australia was once part of Gondwana and the architecture and history of the Phanerozoic sedimentary basins were largely determined by the breakup of that supercontinent. Different types of basin can be recognised and related to the plate tectonic model. Most of the oil and gas in the State occurs in pullapart basins (e.g. Perth and Carnarvon Basins) which formed along the breakup zone. The State's only coalfield is in a rift basin (Collie Basin). Experience elsewhere in the world suggest that downwarp (Bonaparte Basin) and complex (Canning Basin) basins are highly prospective for petroleum. Rift and pullapart basins probably have the best potential for coal.

Introduction

Petroleum, that is oil and natural gas, and coal provide the bulk of the world's energy, e.g. in 1980 they supplied 90% of the energy in the OECD countries (International Energy Agency 1982). Together they comprise the fossil fuels which are those derived from fossil organisms, mostly single-celled marine plants and animals in the case of oil and gas, and land plants in the case of coal. Since fossil fuels are derived from organisms it is natural to explore for them in those rocks which contain abundant organic remains. Such rocks were laid down in sedimentary basins and more especially sedimentary basins formed during the Phanerozoic Era which started about 570 million years ago. Precambrian rocks, while not obviously fossiliferous, do contain evidence of life in them and should not be excluded entirely in the search for fossil fuels.

In following the theme of basins and barrels I shall look first at continental drift and then at the change in thinking about the earth called plate tectonics; then I shall say something about the Gondwana supercontinent by way of setting the scene for a survey of the sedimentary basins of Western Australia, which was once a part of Gondwana. Finally I shall briefly examine the fossil fuel potential of the State's sedimentary basins.

Continental drift

The earth has variously been thought of as a rigid and permanent, with continnents and oceans fixed in their present position for all time, expanding, or contracting. The folded rocks seen in mountain chains such as the Alps suggested contraction, to some, by analogy with the wrinkled skin on a drying apple. Contraction ideas usually went hand in hand with the so-called tetrahedral theory (see Holmes 1964, Carey 1976). A sphere, which has the greatest volume for a given surface would, it was reasoned, contract to a tetrahedron, which has the smallest volume for a given surface. The tetrahedron was usually oriented with one face uppermost representing the Arctic Ocean; the other faces are the three great oceans (Pacific, Atlantic and Indian). The edges and corners represent the land masses. One of the most recent supporters of the theory was W. G Woolnough (1946), the first Professor of Geology at the University of Western Australia. The theory has no followers today, although it does epitomize the asymmetrical distribution of land and sea.

Earth expansion is associated particularly with one of this Society's members, Professor S. W. Carey of Tasmania. While there are certain attractions to the idea of an expanding earth (Carey 1976), the physical difficulties entailed are formidable and the theory is not widely held.

A fixed diameter earth is by far the simplest model to adopt. Again, simplicity suggests that continents and oceans have always been as they are today—witness the lack of granite in ocean basins and the absence of true deep sea sediments on the continents. But the idea of continents moving over the face of the earth—continental drift—has always fascinated some. In its fully developed form the theory is associated with the German meteorologist Alfred Wegener who published "Die Entstehung der Kontinente und Ozeane" in 1915, later translated as "The origin of continents and oceans" (Wegener 1966). However, the idea appears to go back to Francis Bacon (Holmes 1964). The evidence in support of continental drift includes:

a. the fit of the continents like pieces from a jig-saw puzzle, the best example being the fit of Africa and South America.

b. various geological similarities on the continents. As Arthur Holmes (1964), in his class text on physical geology remarks ". . . . the westward convergence across Europe of the outer Caledonian and Hercynian fronts, until they almost meet in the south-west of Ireland, is continued in North America, where the fronts eventually cross". The many similarities between the geology of the southern continents are mentioned below.

c. past climates; for example there is abundant evidence of glaciation in what are now tropical latitudes.

d. plant and animal distributions; these are often much easier to understand if distant continents were once closer together. For example, the Early Cambrian trilobite faunas of North America and Europe; north west Scotland has an "American" fauna, while east Newfoundland and Nova Scotia have a "Welsh" fauna. (Cowie 1971).

While the evidence may be suggestive, the lack of a convincing mechanism to move the continents was a problem. Wegener invoked the gravitational attraction of the equatorial bulge to account for the Polflucht or Flight from the Pole of the continents and the breakup of Pangaea—the one landmass into which he believed all the continents were aggregated. However, physicists, especially Sir Harold Jeffreys (see Jeffreys 1976), pointed out that the force was many times too small. And so, for much of the pre-war years continental drift was out of favour.

Plate tectonics

After the second world war two important developments took place, which helped to change this; palaeomagnetism and marine geology.

Palaeomagnetism is the study of fossil magnetism (Irving 1964). Through a variety of techniques the remnant magnetism of a rock can be determined; this is the magnetic polarity imposed on a rock when the contained iron minerals formed or were deposited. From the measurement of the remnant magnetism the latitude of the magnetic pole at various times in the past can be determined. It was shown by this work that the magnetic pole has not always been where it is now. In fact polar wandering paths can be drawn showing how the position of the pole has changed systematically during time. Moreover, the polar wandering paths for North America and Europe differ and differ more markedly the further back in time one goes (Fig. 1). This led Runcorn to suggest that North America and Europe must have been closer together in Permian times and gradually moved apart in the Mesozoic and Tertiary to their present positions (see Hospers and Van Andel 1970). Another feature is that magnetic polarity has not remained constant but that periods of normal (present day) polarity have alternated with periods of reversed polarity (when the north pole has flipped to become the south pole).

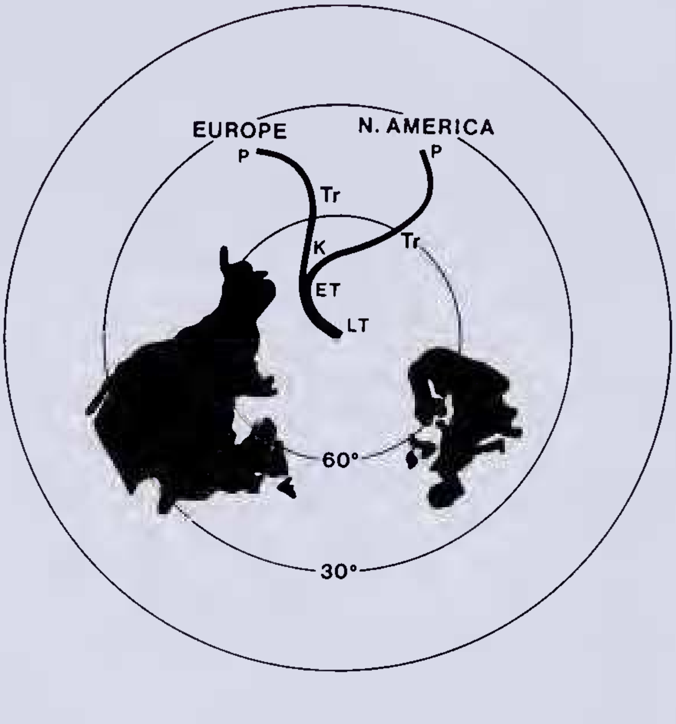

Figure 1.—Apparent polar-wandering paths for Europe and North America. P., Permian; Tr, Triassic; K, Cretaceous; ET, Early Tertiary; LT, Late Tertiary (after Irving and Robertson 1969).

Marine geology, like most oceanography, can be said to have started with the 1873-76 expedition of HMS Challenger, which called in at Fremantle on its epic voyage around the world. However, the science developed dramatically in the 1950s and 60s. Amongst the many interesting findings the following are pertinent.

Heezen, Ewing and others mapped a world-wide oceanic ridge system (Heezen and Fox 1966). This is best developed in the Atlantic Ocean, a submarine mountain chain which occasionally rises above sea level e.g. in Iceland, the Azores, St Paul's Rocks, Ascension. There is a rift valley running along the axis of the ridge and heat flow beneath the axis is much higher than elsewhere in the ocean; the ridge is also a focus of seismic activity.

The ocean basins were found to be quite young. No rocks older than Jurassic were discovered on the ocean floor. An earlier observation was confirmed, namely that the deepest parts of the oceans were the trenches which were situated at the margins of the ocean basins.

All this led Hess (1962) to put forward the idea of sea-floor spreading. In each ocean the mid oceanic ridge is the site of the ascending limb of a convection cell in the mantle which then turns and flows under the oceanic crust carrying the ocean floor with it as on a conveyor belt, and descends into the mantle under the marginal trench.

This idea was confirmed in a remarkable way by the magnetic stripes (Fig. 2). These are linear bands of alternate positive and negative magnetic

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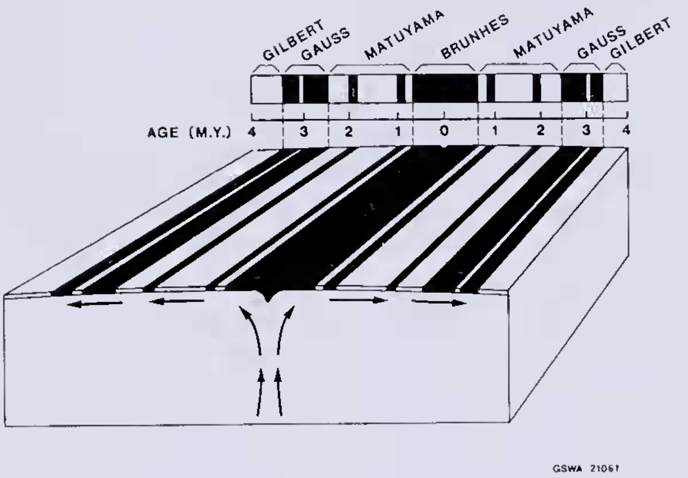

Figure 2.—Sea-floor spreading and the magnetic polarity time scale (after Cox *et al.* 1967).

anomalies which were mapped on the sea floor parallel to the axis of the oceanic ridge system (Vine and Matthews 1963). It was hypothesised that these anomalies are a record of the succesive magnetic reversals, alluded to earlier, and that they can be used to determine the age of the oceanic crust. Many workers have subsequently documented the magnetic anomalies and age of the crust throughout the world's oceans (see McCracken 1979 for a map of the magnetic anomalies around Australia).

The last contribution I shall mention is that of J. T. Wilson (1965) who recognised a new type of fault he termed a transform fault. These are linear discontinuities which offset the oceanic ridge system and magnetic stripes. They resemble transcurrent (lateral displacement) faults but movement along them is in the opposite direction to transcurrent movement. Subsequently, studies of earthquakes along the oceanic ridge system demonstrated that this paradoxical sense of motion was correct; this is because the sea floor itself is moving (spreading) on either side of the transform.

Around 1967 these observations were integrated into a unified theory which has come to be called plate tectonics and is associated with the names of Morgan, McKenzie and Le Pichon (see Hallam 1973). The earth is divided into a number of rigid plates (six in the simplest version of the theory, Figure 3). The margins of the plates (Fig. 4) are either spreading centres (oceanic ridges where new crust is formed), subduction zones (trenches where crust is consumed) or transform faults (where plates slide past each other). Any three plates meet at triple junctions which are various combinations of spreading centres, subduction zones and transform faults meeting at a point.

The theory provides an elegant explanation for a number of puzzling features. It explains why the ocean basins are young—they have only recently been formed; ancient oceanic crust has disappeared into the mantle being consumed in the so-called subduction zones beneath the trenches. Mountain chains form where two plates collide, indeed they represent the suture lines along which plates have joined e.g. the Alps were formed when the African plate collided with the European plate. Finally it provides a mechanism for continent to drift—on the back of plates, driven as it were, by convection cells in the mantle.

While the theory is a powerful one it does have its critics. The Meyerhoffs have written at length detailing palaeoclimatological and plant and animal distribution data which are hard to fit into the plate tectonic model (Meyerhoff and Meyerhoff 1972). Carey (1976), while supporting (and indeed anticipating) some aspects of plate tectonics does not accept the trenches as subduction zones. Of course with an expanding earth, as he advocates, there is no need for subduction zones where crustal material is destroyed.

Retrospect

Plate tectonics has brought about a new way of looking at the earth—the "new global tectonics"—so much so that text books which do not mention the theory are considered dated if not obsolete.

Thomas Kuhn (1962), the philosopher of science, has characterised science as progressing not gradually but through a series of revolutions which overturn, as it were, previously established viewpoints (or paradigms as he calls them) and substitute a new one. Typical examples of revolutions are the Copernican theory that the sun is the centre of the universe and Darwin's theory of evolution through natural selection. In this sense plate tectonics can be regarded as a revolution, although as Hallam (1973) observes it is not entirely clear what paradigm was replaced by the theory although it was probably some notion of continent and ocean permanency. From the philosophical point of view it is interesting to observe, with Hilary Putnam (1974), that Kuhn's idea of science implies that some scientific theories cannot be overthrown by data alone but only by alternative theories.

The revolutions are separated by periods of relative tranquillity. In Kuhn's words "Each intervening period of relative tranquillity, each period of "normal science", is characterised by widespread adherence to whatever theory is current and by the engagement of almost all the scientists in the exploration and articulation of that theory and its ramifications" (quoted in Carey 1976). This "normal science" is well characterised by Sir Macfarlane Burnet (1970) who, in his book "*Dominant Mammal*", recounts "It is illuminating to watch how, as soon as a new phenomenon is recognised in any field of science there is a swift mobilization of dozens or hundreds of scientists who can cheerfully leave their current research activity to join in the gold rush".

For all the "dozens and hundreds" of scientists working in the periods of normal science, I suggest there is merely a handful contributing to the revolutions. In Thomas Carlyle's sense these are the Heroes of Science. Indeed one could paraphrase his remark "the history of the world is but the biography of great men" (Carlyle 1840) and apply it to Kuhnian revolutions.

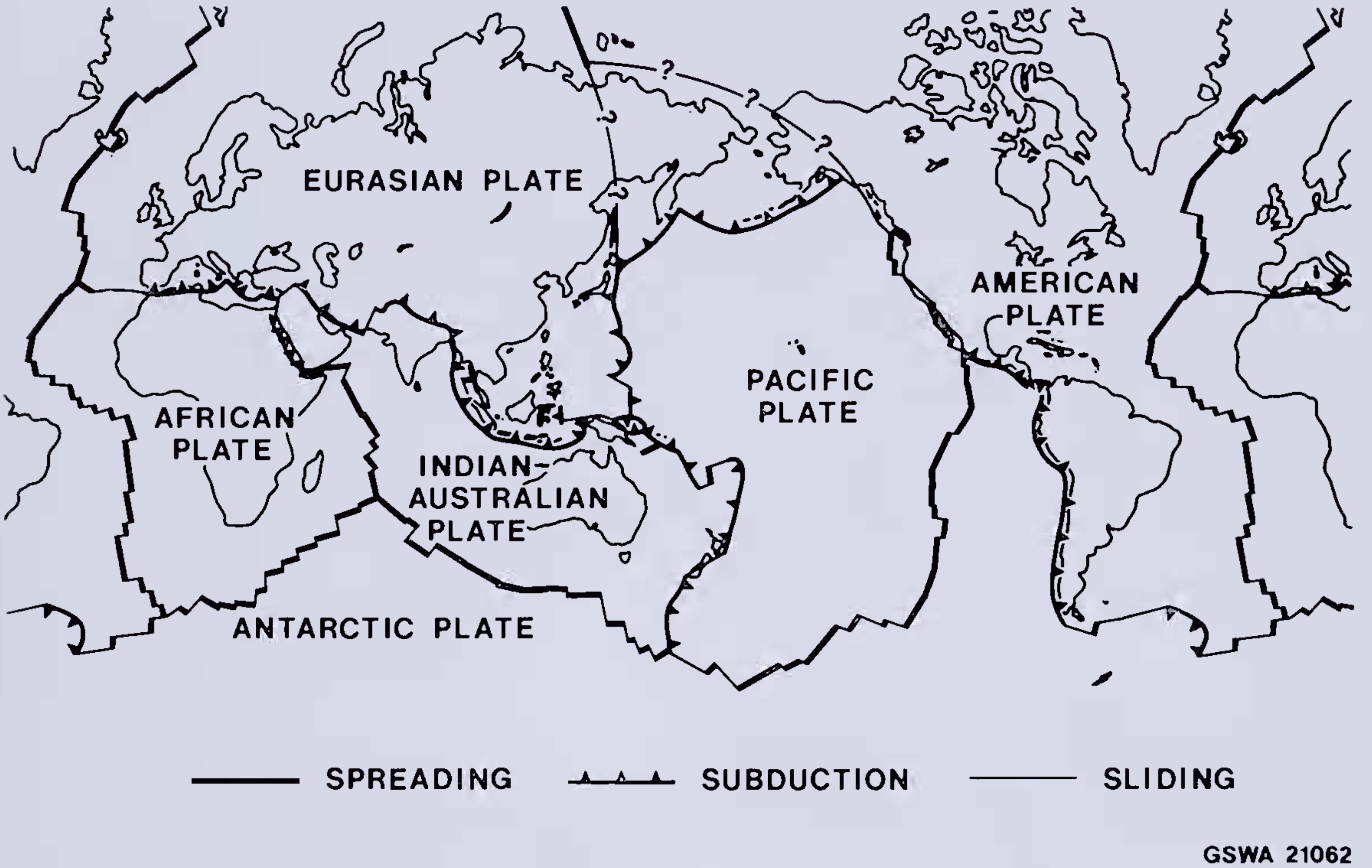

Figure 3.—The six major plates on the earth's surface (after Hamilton 1979).

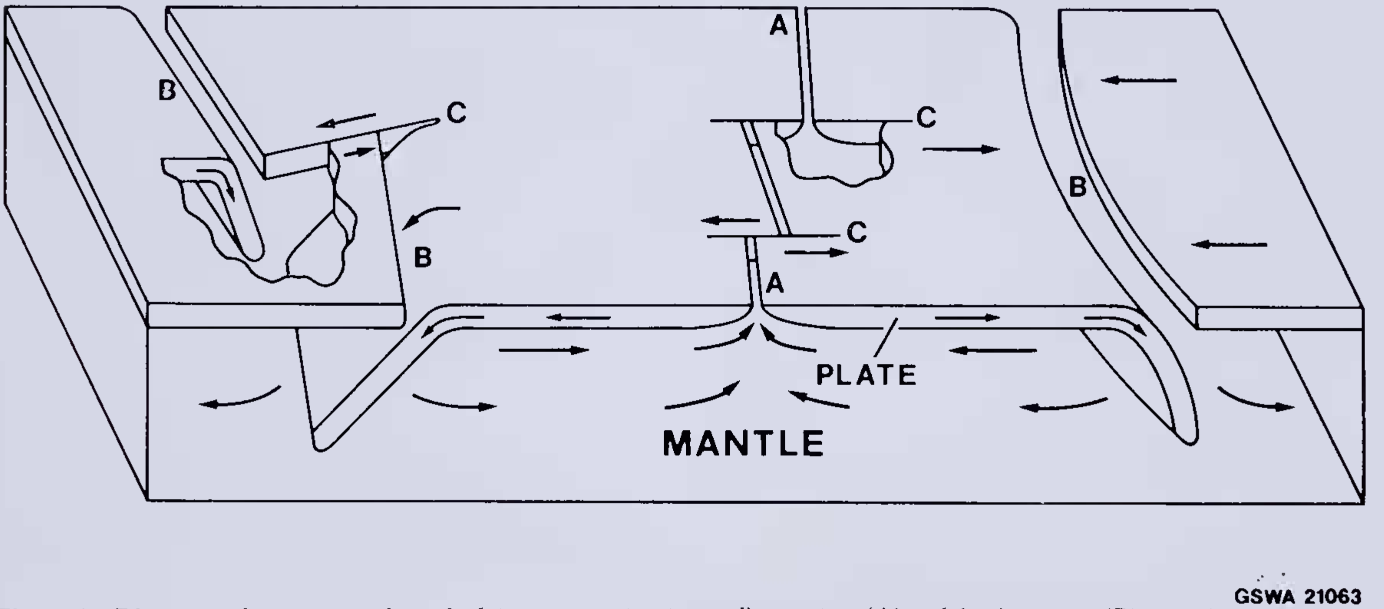

Figure 4.—Diagrammatic representation of plate movements at speading centres (A), subduction zones (B) and along transform faults (C) (after Isaacs *et al.* 1968).

Gondwana

Gondwana—the word means "land of the Gonds" (who inhabited India) and hence the oft-used term "Gondwanaland" is tautologous (Bates and Jackson 1980)—is the name given to the supercontinent embracing South America, South Africa, India, Australia and Antarctica. Curt Teichert, an overseas member of the Society who was at the University of Western Australia in the 1930s and 40s and not a supporter of Gondwana, has written "... it has always seemed an intriguing concidence that the Gondwanaland concept was born exactly one hundred years after Captain James Cook had returned (in 1775) from his second voyage around the world. It was on this voyage that the age-old geographical phantasies of a Terra Australis were finally disproved" (Teichert 1958).

But Terra Australis did exist—many millions of years previously.

The name Gondwana is also applied to a series of rocks in peninsular India which are now known to be Late Carboniferous to Jurassic in age. These rocks are remarkably similar to rocks in South America (the Santa Catharina System), South Africa (the Karroo System), Australia and Antarctica (see for example, Kummel 1970). Essentially the sequence in all continents starts with glacial deposits of Late Carboniferous and Early Permian age, passes up into shales with coal seams and then into sandstones of fluvial origin which continue into the Triassic and Jurassic. The widespread Western Australian glacial unit (variously known under the names Nangetty, Lyons, Grant, Paterson and Stockton Formations) belongs to this sequence as do the Collie Coal Measures. Furthermore, the *Glossopteris* flora (well seen in the Collie Coal Measures) occurs in these rocks throughout Gondwana. This flora consists of seed ferns and it was the difficulty of explaining its distribution over continents now widely separated by oceans that led Blanford in 1875 to propose the existence of an Indian Ocean continent. The name Gondwanaland was proposed by Eduard Suess in 1885.

These early authors thought that land once existed over what are now the South Atlantic and Indian Oceans and subsequently foundered beneath the waves. But Wegener (1966) and especially the South African geologist Du Toit (1937) envisaged Gondwana as being formed by the southern continents fitting together and later drifting apart. Although the fit of South America and Africa is fairly easy to see, it is not entirely clear how the other continents should be reassembled. In fact a variety of reconstructions is possible (Fig. 5).

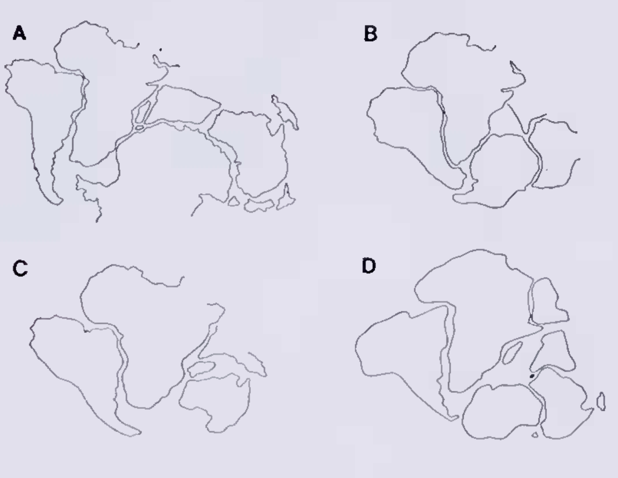

Figure 5.—Reconstruction of Gondwana according to various authors. A, Smith *et al.* (1973) with "Greater India" after Veevers *et al.* (1975); B, Veevers *et al.* (1971); C, Khramov and Petrova (1972); D, Hamilton (1979).

Using several lines of evidence—palaeomagnetism and sea-floor spreading (literally rolling back the sea-floor) it is possible to follow the break up of Gondwana through the Mesozoic. Basically the South Atlantic Ocean started opening in the Early to Mid Cretaceous (Sclater *et al.* 1977), and the Indian Ocean originated in the Late Jurassic to Early Cretaceous (Falvey and Mutter 1981). Recent work (Cande and Mutter 1982) suggests that Antarctica separated from Australia in the Mid Cretaceous and not in the early Tertiary as previously believed.

Western Australia

Western Australia has a land area of 2.5 million km^2. Of this 1 million km^2 are underlain by Phanerozoic sedimentary basins (Fig. 6). In these basins is recorded the history of the Western Australian part of Gondwana and lies the fossil fuel deposits of my title. The other three fifths of the State is underlain by the Precambrian rocks of the shield areas which form the basement on which the Phanerozoic basins were developed.

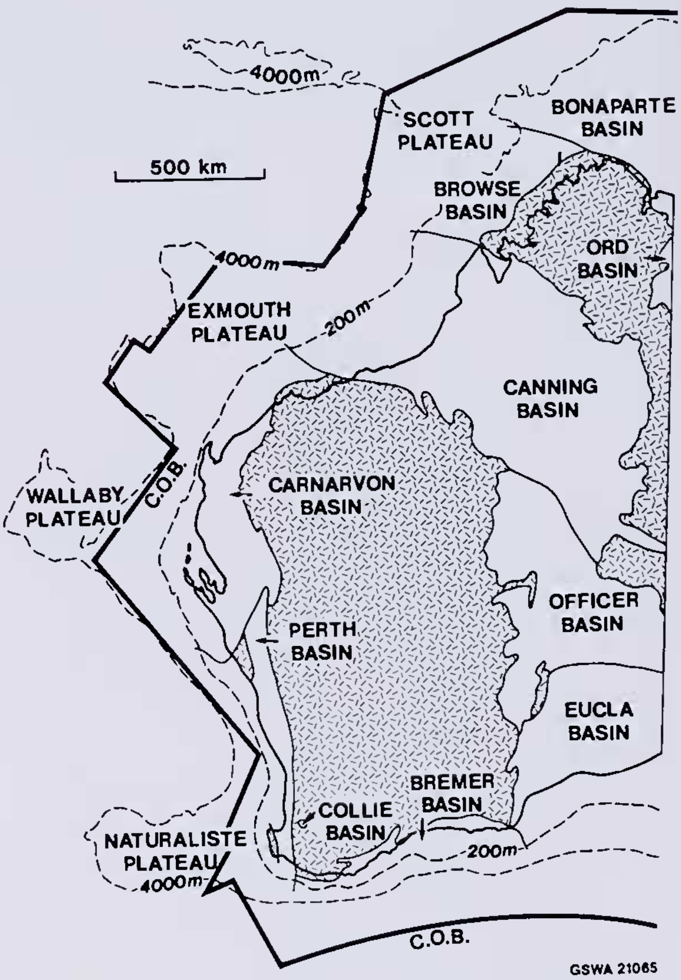

Figure 6.—Phanerozoic sedimentary basins of Western Australia. COB, continent—ocean boundary.

As Figure 6 shows the Phanerozoic basins do not end at the coast but extend onto the continental shelf and beyond; in fact they occupy another 1 million km^2 offshore. The true limit of the basins is at the continent-ocean boundary beyond which oceanic crust created after the breakup of Gondwana occurs (Veevers and Cotterill 1978). Offshore from Western Australia are a number of submarine plateaus, from north to south, the Scott, Exmouth, Wallaby and Naturaliste Plateaus. The Exmouth and probably the Scott Plateaus are underlain by continental crust, the Wallaby and probably the Naturaliste Plateaus by oceanic crust.

The sedimentary basins of Western Australia fall into two obvious groups, those on the Precambrian shield areas (e.g. Officer Basin) and those marginal to the shield (e.g. Perth Basin) which suggests that we can classify basins into various types. This has been done; unfortunately there are as many classifications as there have been classifiers (see, for example, Bally and Snelson 1980, Klemme 1980, Bois *et al.* 1982, Bally 1982). I shall follow the classification of Klemme (1980) who recognises eight basin types of which three are on the shield or craton, and the others are marginal to it. Five of these basin types are present in Western Australia (Table 1). The main features of the Phanerozoic sedimentary basins in the State are summarised in Table 2 and Figures 7 to 14.

Table 1

Classification of sedimentary basins (Klemme 1980)

Basin type	Examples
A. Cratonic basins	
Interior	Officer (WA) Williston (USA)
Complex	Canning (WA, onshore) Pechora (USSR)
Rift	Collie (WA) Sirte (Libya)
B. Marginal basins	
Downwarp	Bonaparte (WA) Arabian basins
Pullapart	Perth (WA) Newfoundland
Subduction	none in WA Indonesian basins
Median	none in WA Maracaibo (Venezuela)
Delta	none in WA Niger

Table 2

Phanerozoic sedimentary basins of Western Australia

Basin	Area (km²,)	Percentage area	Sediment thickness (m)	Age of sediments	Basin type	No. of petroleum exploration wells (*a*)	Wells per 1 000 km²,
Perth	95 000	5	25 000 (*c*)	Proterozoic, Silurian Permian-Cenozoic	Pullapart	90	0·95
Carnarvon	385 000	20	20 000	Silurian-Cenozoic	Pullapart	226	0·59
Canning	530 000	28	15 000	Ordovician-Cenozoic	Complex (onshore) Pullapart (offshore)	127	0·24
Browse	155 000	8	10 000	Permian-Cenozoic	Pullapart	17	0·11
Bonaparte (*b*)	113 000	6	11 000	Cambrian-Cenozoic	Downwarp	19	0·17
Ord (*b*)	15 000	1	1 500	Cambrian, Devonian, Cenozoic	Interior	1	0·07
Officer (*b*)	250 000	13	5 000 (*d*)	Proterozoic, Cambrian, Permian, Cretaceous, Cenozoic	Interior	9	0·04
Eucla (*b*)	320 000	17	1 500	Permian, Jurassic, Cretaceous, Cenozoic	Interior (onshore) .... Pullapart (offshore)	4	0·01
Bremer	62 000	3	200 (*e*)	Cenozoic (*e*)	Pullapart	4	0·06
Collie	225	0·01	1 050	Permian, Cenozoic	Rift	0	0·00

(*a*) drilled to 31/12/1982; (*b*) Western Australian part only; (*c*) Includes 10 000 m of Proterozoic sediments; (*d*) Includes 4 000 m of Proterozoic sediments; (*e*) Onshore part only.

The history of sedimentation in these basins is bound up with the history of Gondwana. To the north of the supercontinent lay the Tethys Sea. Marine transgressions across the Western Australian craton from the north started in the Cambrian and continued intermittently until the Cretaceous. Along the western margin of Western Australia rifting occurred in the Late Palaeozoic in the Perth, Carnarvon and Canning Basins and North-west Shelf area. Subsequently these rifts were filled mainly with clastic sediments. Pullapart started in the mid to Late Jurassic in the north and continued into the Early Cretaceous in the Perth Basin as Australia separated from India; by Late Cretaceous times an open marine environment with carbonate sedimentation was established along the whole western margin.

A similar sequence of events, but with slightly different timing, took place along the southern margin of Western Australia. Rifting probably started in the Jurassic and the pullapart phase commenced in the mid Cretaceous as Australia and Antarctica parted.

The history of the pullapart basins seems to fall into three main phases. These have been called pre-rift, rift and post-breakup by Falvey (1974) and are illustrated in Figure 15. The pre-rift basin is a phase of gentle subsidence. With rising temperature in the mantle, the crust is thinned and rift-valley subsidence begins. The rift valley phase may last a long time and is ended by continental breakup and sea-floor spreading with the formation of new oceanic crust. Cooling of the crust beneath the rift valley causes subsidence with the accumulation of sediments which prograde across the continental margin and form the post-breakup sequence.

Veevers, Jones and Powell (1982) also recognise three phases in the history of the Western Australian basin and have named them pre-Gondwanan, Gondwanan and post-Gondwanan. The pre-Gondwanan phase of early and middle Palaeozoic age they interpret as representing failed rift arms, that is rifts which did not go on to the breakup phase; perhaps the Fitzroy Trough in the Canning Basin and the Collie Basin are examples. The sediments associated with this phase include widespread carbonates (Canning, Bonaparte Basins) and evaporites (Canning, Carnarvon Basins) which suggest deposition in low latitudes. The Gondwanan phase equates with Falvey's rift valley phase and includes the glacials, coals and sandstones of the Gondwana System of Late Carboniferous to Jurassic age, which at least initially were laid down in high latitudes. The post-Gondwanan phase corresponds with Falvey's post-breakup progradation phase.

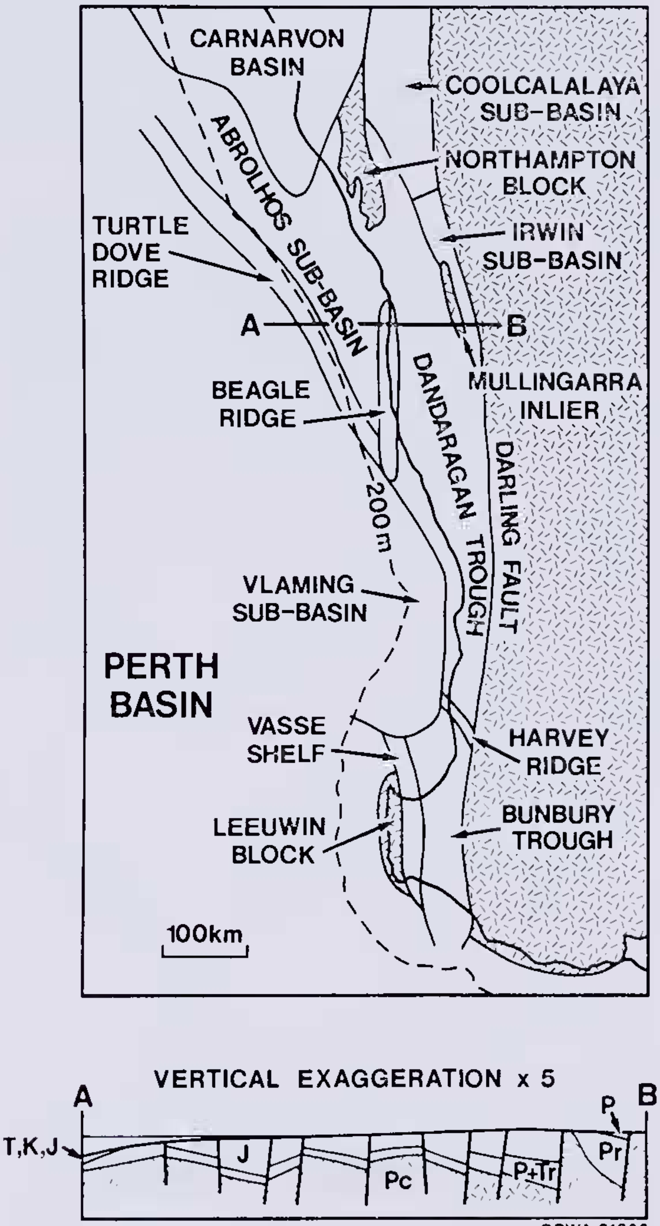

Figure 7.—Perth Basin; subdivisions and cross section (after Playford *et al.* 1976). T, Tertiary; K, Cretaceous; J, Jurassic; Tr, Triassic; P, Permian; Pr, Proterozoic; Pc, Precambrian basement.

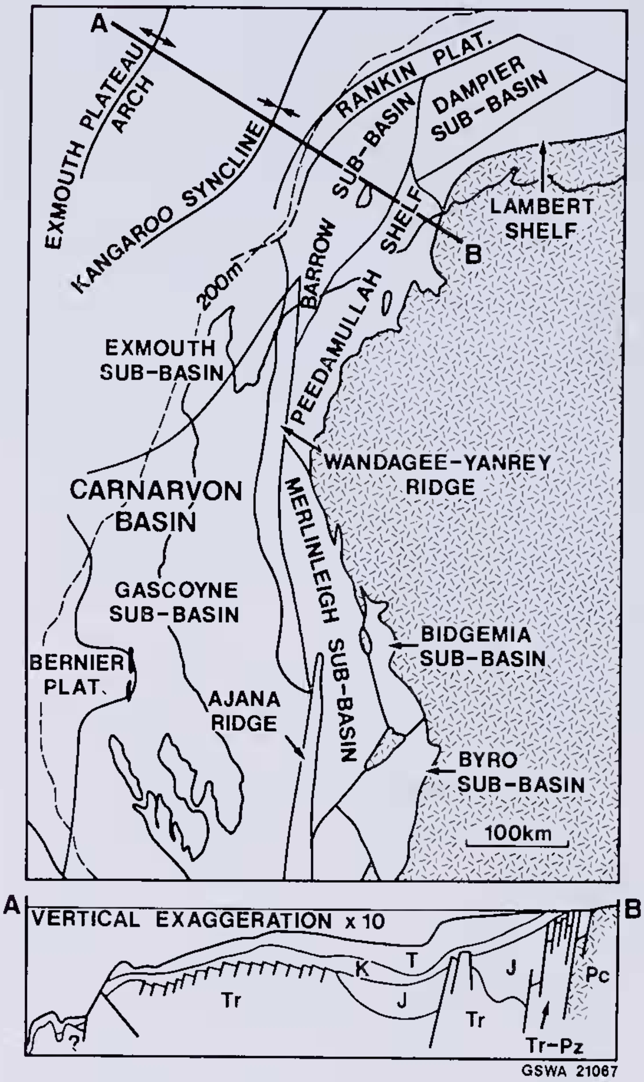

Figure 8.—Carnarvon Basin; subdivisions and cross section (after Falvey and Mutter 1981). T, Tertiary; K, Cretaceous; J, Jurassic; Tr, Triassic; Pz, Palaeozoic; Pc, Precambrian basement.

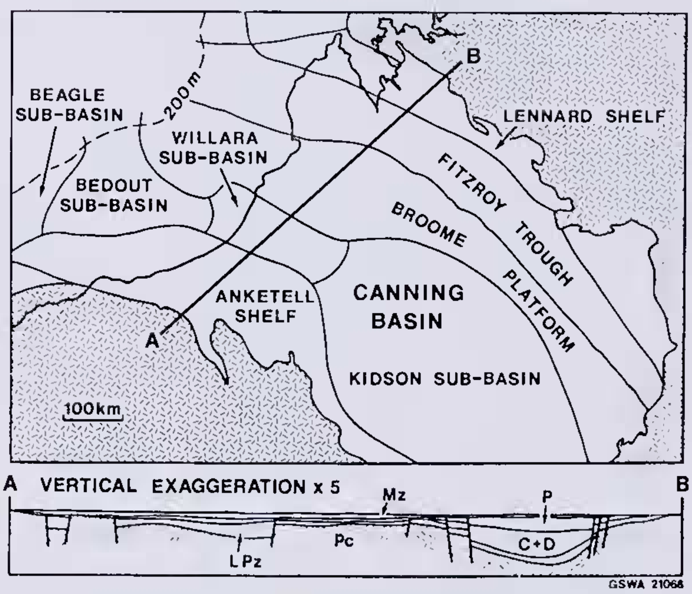

Figure 9.—Canning Basin; subdivisions and cross section (after Playford *et al.*, 1975). Mz, Mesozoic; P, Permian; C, Carboniferous; D, Devonian; LPz, Lower Palaeozoic; Pc, Precambrian basement.

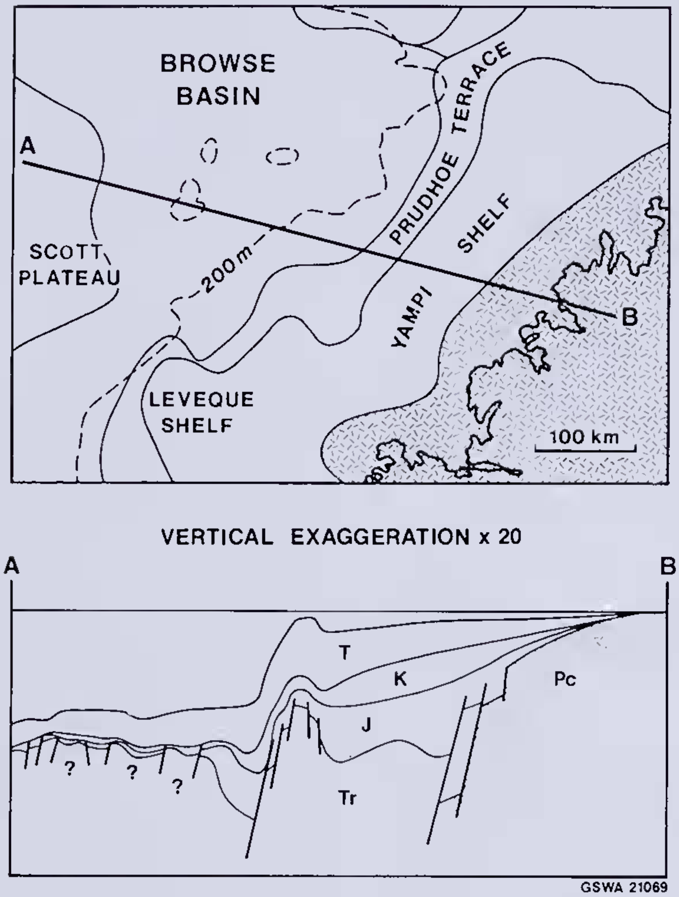

Figure 10.—Browse Basin; subdivisions and cross section (after Falvey and Mutter 1981). T, Tertiary; K, Cretaceous; J, Jurassic; Tr, Triassic; Pc, Precambrian basement.

Fossil fuel potential

The fossil fuel potential of Western Australia is summarised in Figure 16 in which the stratigraphic sequence in each basin is outlined and the main oil and gas shows and coal deposits are plotted.

Proterozoic. The thick section of Proterozoic sediments in the Officer Basin includes evaporites and has a number of diapiric structures. There have been minor shows of oil and gas.

Ordovician. Oil shows in the Ordovician Nita, Goldwyer and Willara Formations have been recorded from the Broome Platform in the Canning Basin.

Devonian. Devonian reef complexes in the Canning Basin produce oil at Blina and in the Bonaparte Basin have yielded shows of oil.

Carboniferous. The Blina field also produces oil from rocks of this age and the Bonaparte Basin oil shows referred to previously are partly from carbonates of this age. In the Canning Basin oil shows have also been encountered in the Lower Carboniferous Anderson Formation.

Permian. Again, in the Canning Basin there are oil shows in the Grant Group which is of Late Carboniferous and Early Permian age. Permian rocks are gas reservoirs in the Bonaparte Basin (Hyland Bay Formation in the Tern field) and Perth Basin (Caryngina Formation in the Woodada field, Wagina Sandstone and Irwin River Coal Measures in the Dongara field). The Permian is the main target for coal exploration, the State's only commercial coalfield, at Collie, being in rocks of this age. Permian coal is also known from the Perth, Carnarvon and Canning Basins.

Triassic. The Dongara field in the Perth Basin produces gas from sandstones of Triassic age and the reservoirs in the Rankin Platform (Carnarvon Basin) and in the Browse Basin are also of this age. Oil is also known from these rocks in the Rankin Platform.

Jurassic. Jurassic rocks are gas bearing in the Perth Basin (mainly Cockleshell Gully Formation), Carnarvon Basin and Browse Basin. The original Barrow Island oil discovery was from the Upper Jurassic, although nearly all the production comes from the Cretaceous. In the Perth Basin coal of this age occurs in the Dandaragan Trough (Eneabba).

Cretaceous. The most prolific reservoirs of Cretaceous age which have been developed are at Barrow Island where the Lower Cretaceous Windalia Sand contains oil. Gas of this age is widely known in the Carnarvon Basin and oil occurs in the Carnarvon and Perth Basins.

Tertiary. Oil and gas are unknown from the Tertiary in Western Australia. Lignite (brown coal) is widespread in the onshore Bremer Basin (near Esperance), western margin of the Eucla Basin and in palaeovalleys on the adjacent Precambrian shield.

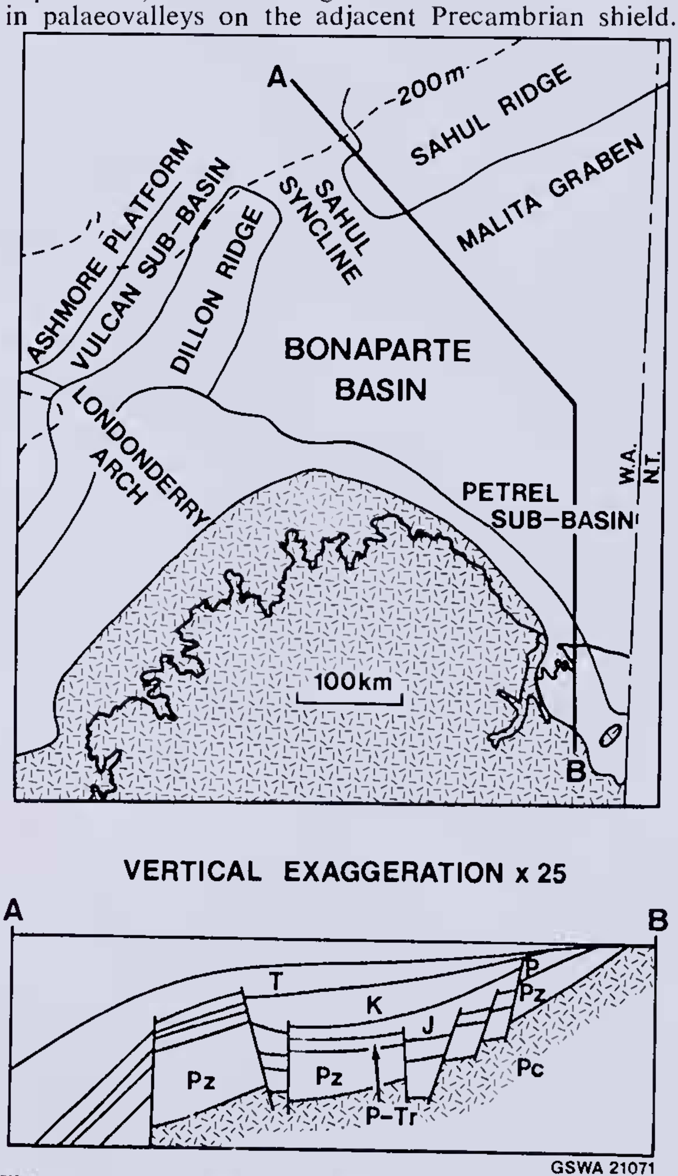

Figure 11.—Bonaparte Basin; subdivisions and cross section (after Doutch and Nicholas 1978). T, Tertiary; K, Cretaceous; J, Jurassic; Tr, Triassic; P, Permian; Pz, Palaeozoic; Pc, Precambrian basement.

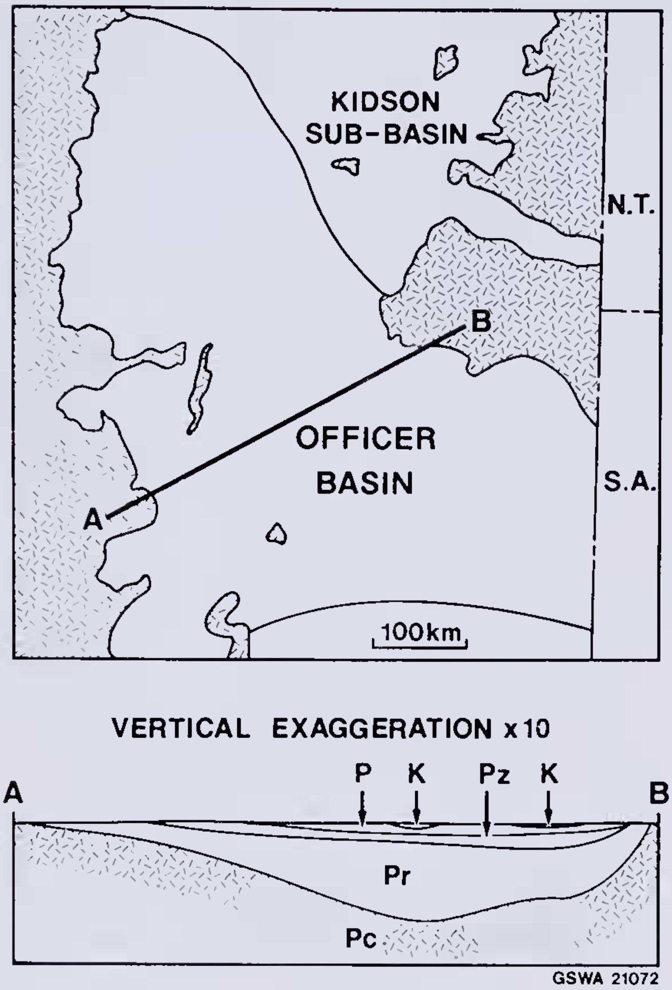

Figure 12.—Officer Basin; cross section (after Jackson and van de Graaf 1981). K, Cretaceous; P, Permian; LPz, Lower Palaeozoic; Pr, Proterozoic; Pc, Precambrian basement.

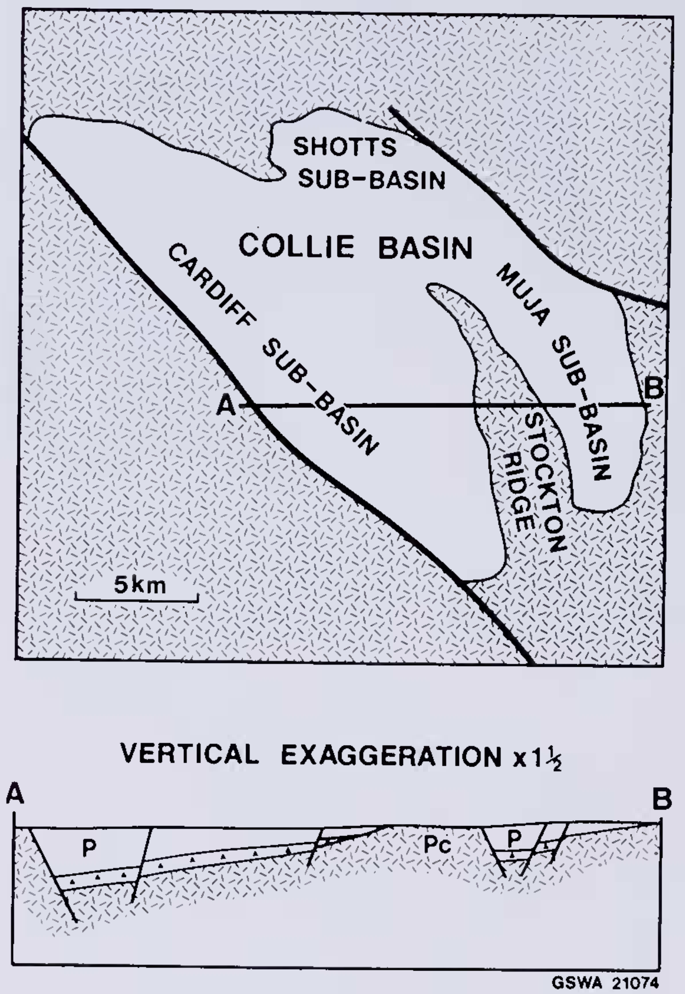

Figure 14.—Collie Basin; subdivisions and cross section (after Lowry 1976). P, Permian (triangles denote glacial sediments); Pc, Precambrian basement.

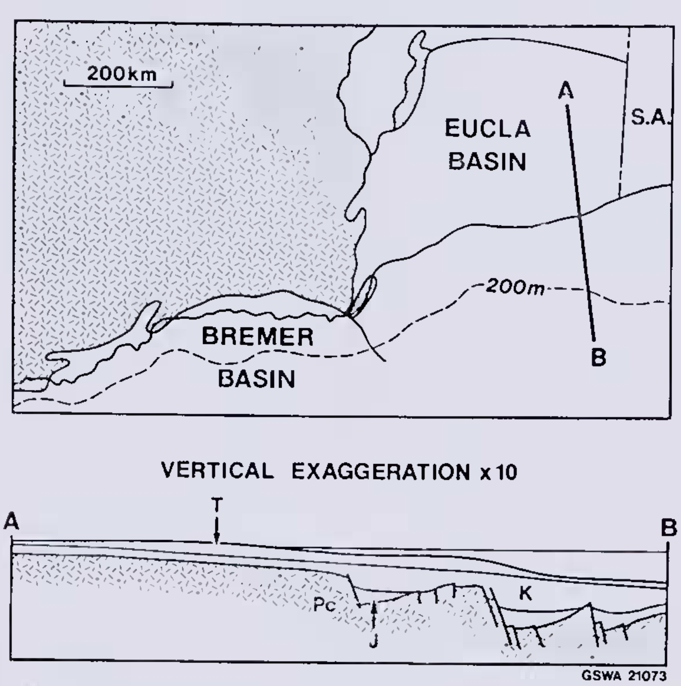

Figure 13.—Eucla and Bremer Basins; cross section (after Bein and Taylor 1981). T, Tertiary; K, Cretaceous; J, Jurassic; Pc, Precambrian basement.

Prospects

Two oil fields and 11 gas fields or potential gas fields have been discovered so far (July 1983), all in the Perth, Carnarvon, Canning, Browse and Bonaparte Basins; the Ord, Officer, Eucla and Bremer Basins have not been sites of hydrocarbon discoveries to date. The only coalfield known is in the Collie Basin, although potential coalfields occur in the Perth and Bremer Basins. Obviously one is tempted to look for hydrocarbons and coal near where existing deposits have been found—indeed this is one of the cardinal rules of exploration. However, the law of diminishing returns sets in and the success rate declines with time. Giant oil and gas fields are usually found in the early stages of exploration in a basin and the same would be true for coal.

The next step is to look at new areas. Where are the new frontiers? One guide is to see what are the most prospective types of basin. This has been done for petroleum by several workers. Klemme (1980) has calculated what percentage of reserves are in different types of basin and the percentage area occupied by each basin type. In Table 3 the column labelled reserves/area ratio summarises his results; a figure greater than 1 indicates a basin

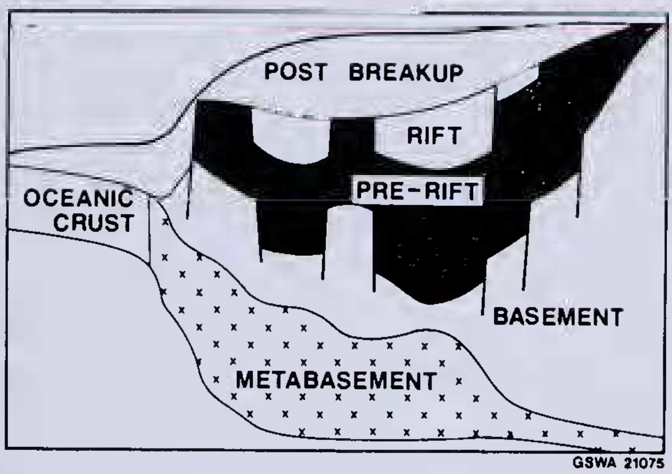

Figure 15.—Diagrammatic cross section of a pullapart basin (after Falvey 1974).

Table 3

Basin types and petroleum reserves (after Klemme 1980)

Basin type		Percentage basin area	Percentage reserves	Reserves/ area ratio
Interior	World	18·2	1·5	·008
	W.A.	31·0	0·0	0·0
Complex	World	27·3	25·0	0·9
	W.A.	22·0	1·0	0·05
Rift	World	5·4	10·0	1·9
	W.A.	0·01	0·0	0·0
Downwarp	World	17·5	47·0	2·7
	W.A.	6·0	2·0	0·33
Pullapart	World	18·2	0·5	0·03
	W.A.	42·0	97·0	2·31
Subduction	World	7·0	7·5	1·1
	W.A.	0·0	0·0	0·0
Median	World	3·7	2·5	0·7
	W.A.	0·0	0·0	0·0
Delta	World	2·6	6·0	2·3
	W.A.	0·0	0·0	0·0

type with a large proportion of the world's petroleum reserves, less than 1 indicates a basin with a small proportion of the reserves. Downwarp basins are by far the most productive, chiefly because they include the giant fields of the Middle East. By contrast pullapart basins are the least productive basins. Yet in Western Australia they have 98% of the oil reserves (the remaining 2% being in complex basins) and 96% of the gas reserves (with only 4% in downwarp basins). Since Western Australia has no delta, subduction, median or rift (except for the non-petroliferous Collie Basin) basins, Klemme's data suggest that downwarp and complex basins are the ones in which exploration should be concentrated, that is the Bonaparte and Canning Basins respectively. Certainly exploration in the Canning Basin has increased dramatically in the last few years, although the Bonaparte Basin still lags behind somewhat in exploration effort.

With coal the situation is less easy to quantify and more difficult to fit into any classification of basin types. Rift and pullapart basins have been the most promising so far. In other parts of Gondwana, rift and cratonic interior basins seem to contain the bulk of the Permian coals. Future exploration will be in the pullapart basins—the Perth Basin for Permian and Jurassic coal, the Bremer and Eucla Basins for Tertiary lignite—and the search for other small concealed rift basins like the Collie Basin will continue on the Precambrian shield.

Conclusions

I have sketched the fossil fuel potential of the sedimentary basins of Western Australia against a global backdrop of drifting continents, ever-changing plates and the breakup of Gondwana. In the latter part of my address I have dealt with what Kuhn would call "normal science". I have deliberately refrained from mentioning the names of the many workers who have contributed to our knowledge of the sedimentary basins. There are few of Carlyle's Heroes here. To quote the historian Hugh Thomas (1981), "The men who made history were enabled to survive by . . . the patient toil of the husbandmen". Normal science is the domain of the husbandman. But this is not to deny that the spirit of creativity is at work here just as it is in times of scientific revolution—for out of the periods of normal science there must arise tomorrow's revolutions.

My immediate predecessor, Professor J. F. Loneragan, entitled his address "Curiosity and practicality in scientific research" and spoke of the interplay of pure and applied science. My theme has ranged from the curious global plates which determine the history of the basins to the practical barrels of oil. And yet regardless of the motivation, whether curiosity or practicality, the search for fossil fuels depends on creative ideas.

I should like to finish by quoting a famous American petroleum geologist, Wallace Pratt; although he had oil in mind when he wrote, his message applies to the exploration for all fossil fuels. "Where oil is first found . . . is in the minds of men. The undiscovered oil field exists only as an idea in the mind of some oil-finder. When no man any longer believes more oil is left to be found, no more oil fields will be discovered, but so long as a single oil-finder remains with a mental vision of a new oil field to cherish . . . just so long new oil fields may continue to be discovered." (Pratt 1952).

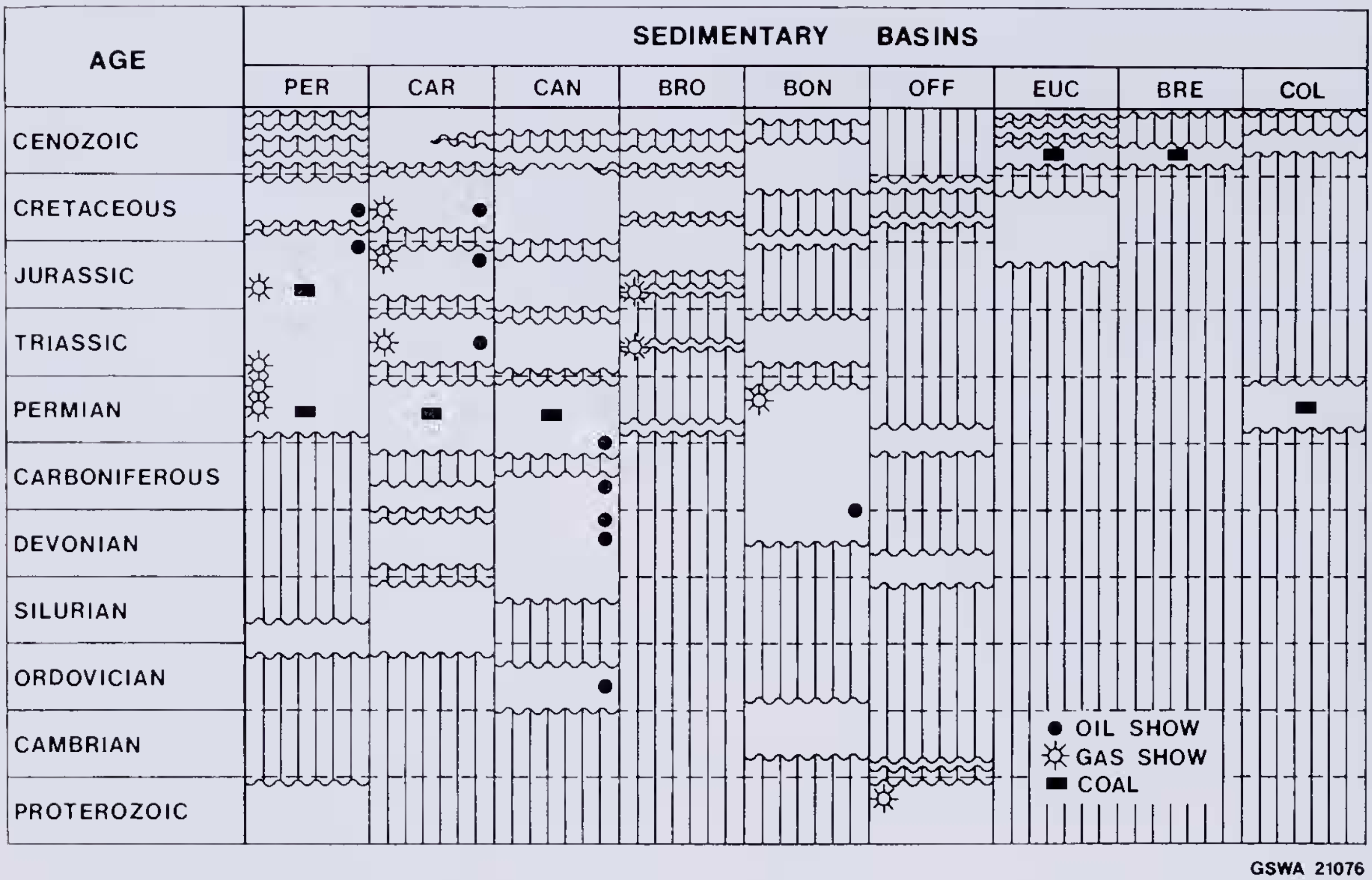

Figure 16.—Simplified stratigraphic sequences in the main Phanerozoic sedimentary basins showing the principal oil, gas and coal occurrences. PER, Perth Basin; CAR, Carnarvon Basin; CAN, Canning Basin; BRO, Browse Basin; BON, Bonaparte Basin; OFF, Officer Basin; EUC, Eucla basin; BRE, Bremer Basin; COL, Collie Basin.

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Chromosome numbers in Western Australian plants, II

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Abstract

Chromosome numbers for 76 species are given. The counts on *Cheiranthera* (n = 12), *Halosarcia* (n = 9), *Pityrodia* (n = 14), *Maireana* (n = 9), *Cypselocarpus* (n = 14) and *Phlebocarya* (n = 7) are first records for these genera.

Introduction

This paper documents chromosome numbers for 76 species of flowering plants from Western Australia. These are nearly all new records for these species.

Materials and methods

These are the same as outlined in Keighery (1978).

Results

Chromosome numbers, details of collection localities and vouchers are given in Table 1. Abbreviations are as given in Keighery (1978). Vouchers are deposited in Kings Park Herbarium and/or in PERTH.

Reference

Keighery, G. J. (1978).—Chromosome numbers in Western Australian plants, I. *Roy. Soc. West. Aust.*, 60: 105–106.

Table 1

Miscellaneous species counted

Taxon	n	2n	Locality	Voucher
MONOCOTYLEDONAE				
JUNCAGINACEAE				
Triglochin minutissima F. Muell.	14	....	Cannington	GK 1277
COMMELINACEAE				
Cartonema philydroides F. Muell.	12	....	12 km N. Port Gregory	GK 1766
HAEMODORACEAE				
Phlebocarya ciliata R. Br.	7	....	10·2 km N. Walpole	GK 679
P. ciliata R. Br.	7	....	5 km S. Carbanup River Store	GK 691
P. filifolia (F. Muell.)	7	....	5 km S.E. of Badgingarra	GK 2552
DICOTYLEDONAE				
PROTEACEAE				
Adenanthos cuneata Labill.	13	....	Gnowangerup Shire Boundary on Ravensthorpe Road	GK 229
A. forrestii F. Muell.	13	....	Twilight Cove	GK 232
A. gracilipes A. S. George	13	....	32° 33'S, 120° 20'E	GK 1513
A. obovata Labill.	13	....	7 km S. Collie	GK 198
A. oreophila Nelson	13	....	Mt. Ragged	GK 266
A. sericea Nelson ssp. sphalma Nelson	13	....	Hellfire Bay	GK 474
Grevillea bipinnatifida R. Br.	10	....	Welshpool Road	GK 1980
G. pterosperma F. Muell.	10	....	2 km W. Mt. Hampton	GK 23
G. sp. nov.	10	....	Duladgin Rock	GK 1773
Hakea coriacea Maconochie	10	....	2 km W. Mt. Hampton	GK 23, a
Persoonia angustiflora Benth.	7	....	10 km N. Mt. Holland	GK 1078
P. striata R. Br.	7	....	3 km W. Tamin	GK 1984
P. teretifolia R. Br.	7	....	32° 33'S, 120° 20'E	GK 1512
P. sp.	7	....	7 km N. Howatharra	GK 185
CHENOPODIACEAE				
Atriplex bunburyana F. Muell.	9	....	Twilight Cove	GK 228
Sclerolaena drummondii (Benth.) Domin	9	....	24 km S. Yellowdine	GK 14
Chenopodium pseudo-microphyllum Aellen	9	....	14 km Ravensthorpe	GK 662
Halosarcia lylei (Ewart et White) P. G. Wilson	9	....	Mortlock River, Meckering	GK 390
Halosarcia lepidosperma P. G. Wilson	....	18	Pallinup River	GK 671
Maireana sclerolaenoides (F. Muell.) P. G. Wilson	9	....	Karolin Rock	GK 11
M. trichoptera (F. Muell.) P. G. Wilson	9	....	Karolin Rock	GK 12
Rhagodia preissii Moq.	9	....	14 km W. Ravensthorpe	GK 663

Taxon	n	2n	Locality	Voucher
GYROSTEMONACEAE				
Codonocarpus cotonifolius Desf.	14	....	2 km N. Millstream	GK 759
Cypselocarpus haloragoides F. Muell.	14	....	Bremer Bay	GK 846
Gyrostemon ramulosus Desf.	14	....	25 km N. Neale Junction	GK 562
RANUNCULACEAE				
Ranunculus colonorum Endl.	8	....	Mt. Chudalup	GK 683
BRASSICACEAE				
Lepidium linifolium (Desf.) Benth.	16	....	Quobba	Demarz 3871
Stenopetalum filifolium Benth.	....	10	10 km S. Waialki	GK 380
S. filifolium Benth.	....	10	32 km S. Yellowdine	GK 393
PITTOSPORACEAE				
Billardiera floribunda (Putterl.) F. Muell.	12	....	Augusta	GK 1569
Cheiranthera filifolia Turcz. var. *brevifolia* Bennett	12	....	28 km W. Ravensthorpe	GK 665
FABACEAE				
Bossiaea preissii Meisn.	9	....	2 km W. Israelite Bay	GK 219
Burtonia conferta DC.	9	....	115 km N. of Perth	GK 364
B. viscida E. Pritzel	9	....	8 km N. Southern Cross	GK 9
Daviesia croniniana F. Muell.	9	....	20 km S.W. Marvel Loch	GK 22
D. epiphylla Meisn.	9	....	Strathmore Road to Cervantes	GK 1793
D. hakeoides Meisn.	9	....	50 km S. Nannup on Brockman Hwy	GK 353
D. polyphylla Benth. ex Lindl.	9	....	31 km N. Perth on Toodyay to Calingiri Rd	GK 108
D. preissii Meisn.	9	....	10 km S. Stuart Rd Brockman Hwy	GK 353
D. striata Turcz.	9	....	3 km N. Regans Ford	GK 288
D. striata Turcz.	9	....	16 km along Cadda from Nair Road	GK 1983
Crotalaria cunninghamii R. Br.	8	....	Karratha	GK 2362
Gompholobium aristatum Benth.	9	....	131 km N. Perth	GK 355
G. ovatum Meisn.	9	....	10 km S. Stuart Road on Brockman Highway	GK 352
G. sp.	9	....	Walyunga	GK 200
Isotropis cuneifolia (Sm.) Benth. ex B. D. Jackson	18	....	St. Columba College	GK 1819
Jacksonia alata Benth.	9	....	7 km W. Toodyay	GK 1053
J. furcellata (Bonpl.) DC.	9	....	7 km N. Howatharra	GK 184
J. horrida DC.	9	....	Windy Harbour	GK 991
J. namatoclada F. Muell.	9	....	Charles Gairdner Reserve	GK 325
J. restioides Meisn.	9	....	7 km W. Toodyay	GK 1052
J. restioides Meisn.	9	....	7 km E. Mawson	GK 294
J. umbellata Turcz.	9	....	2 km S. Mt. Ragged	GK 437
J. sp. 1	9	....	Munglinup	GK 620
J. sp. 2	9	....	Tarin Rock Siding	GK 368
Kennedia carinata (Benth.) Domin	11	....	50 km W. Condinup	GK 222
K. glabrata (Benth.) *Lindl.*	11	....	Cult—ex Mt. Chudalup	GK sn
K. macrophylla Meisn.	11	....	Cape Leeuwin	GK 1887
K. stirlingii Lindl.	11	....	Bindoon Hill	GK 101
Mirbelia dilatata R. Br.	8	....	South Ironcap	GK 887
Oxylobium lanceolatum (Vent.) Druce	8	....	2 km W. Two People's Bay	GK 1390
O. parviflorum Benth.	8	....	Sandalwood Rd, S.E. Stirling Ranges	GK 356
Pultenaea adunca Turcz.	7	....	47 km S. Ravensthorpe	GK 633
P. capitata (Turcz.) Druce	7	....	7 km S. Winchester	GK 1057
Swainsona sp.	16	....	Gnarlbine Rock	GK 500
GERANIACEAE				
Pelargonium australe Willd.	11	....	Mt. Madden	GK 1938
P. littorale Hueg.	11	....	Lort River	GK 1389
ZYGOPHYLLACEAE				
Zygophyllum fruticulosum DC.	8	....	Red Bluff	GK 1792
RUTACEAE				
Diplolaena ferruginea P. G. Wils.	14	....	Cockleshell Gully	GK 202
D. microcephala Bartl.	14	....	Forrest Beach, Capel	GK 32
BORAGINACEAE				
Halgania lavandulacea Endl.	16	....	Twilight Cove	GK 238
CHLOANTHACEAE				
Pityrodia terminalis (Endl.) A. S. George	14	....	16 km E. Mt. Hampton	GK 37
BRUNONIACEAE				
Brunonia australis R. Br.	9	....	Comet Vale	GK 337